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Radar Echoes from Atmospheric Inhomogeneities

by

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1. Introduction and Summary

Radar echoes have been received using the 10 cm. radar equipment at East Hill in weather conditions which make it certain that the echoes were not received from raindrops or cloud formations. It is also unlikely that the echoes were received from solid objects (aircraft, birds, insects etc.), although they were usually similar to echoes from such objects, and it is thought that they were the result of back-scattering of radio energy from discontinuities in refractive index of portions of the atmosphere. The gradients of temperature and/or vapour pressure which are necessary to give the requisite echo intensity are much greater than have been observed so far, but observations on a sufficiently fine scale have not yet been made.

The upper limit of the height at which echoes were observed was frequently the height at which an inversion or isothermal layer probably occurred.

Observations of the movement of the echoes showed that they moved in the direction of the probable wind at their height but with speeds in excess of the wind speed.

2. The observations

Details of the radar echoes which are the subject of this paper, and other relevant information from the Daily Weather Report and Daily Aerological Record, are listed in Table I.

The echoes usually took the form, when seen on the PPI display, of a number of small dots, more or less evenly distributed around the station, similar to those received from small aircraft (see photograph (i)). The height-range display (photograph (ii)) showed the echoes to be usually confined to a fairly narrow and horizontal belt with the top on most occasions at 5,000 ft. or below. The vertical spread of an individual echo was no greater than would be expected, because of the beam-width in the vertical, of an echo from a point source (compare aircraft echo at 25,000 ft. in photograph (ii)).

The angle of incidence of the radar beam did not appear to be of importance since the echoes were visible at very short ranges, with the beam elevation 15 to 19 deg., on the height-range display as well as at ranges greater than 30 miles when the beam was almost horizontal. On one occasion (photograph (iii)) two such belts of echo were seen, the higher layer having a top about 8,000 ft. These observations make it impossible that the effects observed are related to anomalous propagation which requires the presence of a radio duct into which

/radar

radar energy is fed at glancing angles. (A number of occasions when echoes were observed which the height-range display showed to be near zero degrees elevation have not been considered in this report).

Table I shows that the echoes were observed under different weather conditions ranging from completely cloudless to mainly cloudy. There was a marked tendency, if the echoes were observed during the afternoon, for the number of echoes to increase considerably in the period around sunset and remain numerous up to the latest time of observation. On one occasion, 5th March, 1952, the number of echoes increased so much during the late evening as to give almost continuous echo to ranges beyond 20 miles on the PPI display (photograph (iv)) and yet on this occasion there was probably little or no cloud over a large part of the area. The height-range display (photograph (iii)) showed the echoes to be in two distinct layers.

The speed of movement of the echoes was measured on several occasions by taking time exposures of the PPI display tube and noting the time of revolution of the aerial. Four or five revolutions of the aerial were usually taken giving an exposure time of two to five minutes. An example of a photograph taken in this way is given in photograph (v) from which it is clear that the individual echoes lasted for at least the duration of the photographic exposure and from which it is possible to measure the direction of movement of the echoes and, from the spacing between the separate "blips", their speed. Speeds obtained in this way are also shown in Table I together with the most probable value of the upper wind at the height of the echoes. It will be seen that the echoes usually moved from the approximate direction of the wind but at a greater speed.

Also shown in Table I are the heights of any inversions or isothermal layers in the Larkhill and Hemsby radiosonde ascents closest to the times of observation. East Hill is about half way between Larkhill and Hemsby so that, when the time of the radiosonde ascent relative to the time of observation is also taken into account, it is not possible to be certain of the detailed structure in the area from which echoes were received. Nevertheless there is some indication that a markedly stable layer existed at about the maximum height from which echoes were received.

3. Similar observations in America

Echoes of the kind described here have been referred to as 'angels' in American literature and the various observations made on vertically looking, automatic tracking radar and PPI have been summarised by Goldstein (1).

On vertically looking radar the echoes appeared most frequently as isolated signals at ranges up to several thousands of yards and lasting a fraction of a minute. They were more numerous on calm summer nights and have been detected on wavelengths from 10 cm. down to 1cm. Similar echoes have been obtained with 'sonars' using sound wavelengths of the same order of magnitude as the radars. The PPI echoes are described as giving a stippled dot pattern at ranges up to 20 miles and seemed especially prominent after sunset. The echoes moved irregularly with speeds up to 20 mph.

There is no doubt that the echoes seen in America were exactly similar to those reported in this paper.

4. Discussion of the observations

A very thorough discussion of these echoes has been given by Goldstein (1) who considers that many echoes can be explained in terms of birds, insects, second trace echoes and side-lobes. He does recognize, however, a residuum of observations that cannot be accounted for in this way and for which the only explanation would appear to be atmospheric inhomogeneities. It is considered that the observations reported here must also be explained in this way, since birds and insects are unlikely to be found at the heights, and in the numbers, observed after dark and in the winter while second trace echoes are unlikely to

be symmetrically distributed round the station at such high angles of elevation. Side-lobes, which may be the explanation of some echoes on vertically looking radar, cannot be the explanation with the equipment used here.

The simplest type of atmospheric inhomogeneity is a uniform gradient of refractive index starting at a distance R from the radar and ending at R + δR and extending over an area A perpendicular to the direction of the radar beam. For such an inhomogeneity Goldstein(1) shows that the effective radar cross-section, σ , is given by:

$$\sigma = \frac{A^2}{4\pi}\left[\frac{d(n-1)}{dR}\right]^2 \sin^2\left[\frac{2\pi\delta R}{\lambda}\right] \quad \text{.....(I)}$$

where n is the refractive index and λ the radar wavelength. He quotes a largest observed value of $\frac{d(n-1)}{dR}$ in one experiment of $2.10^{-7} m^{-1}$ which would produce a radar cross-section of 10^{-6} m^2 if over an area 150 m. square. This was considered much too large an area since it implies a surface of inhomogeneity of this size at right angles to the radar beam with distances of all points on the surface from the radar the same to within a wavelength (10 cm. or less).

It is clear however that measurements so far made do not enable $\frac{d(n-1)}{dR}$ to be determined for small values of δR of the order of $\lambda/4$ (which value of δR makes σ a maximum) and it is interesting to find what values of A and $\frac{d(n-1)}{dR}$ would give the echoes observed, supposing each echo to come from a single inhomogeneity. From the characteristics of the equipment used the equivalent echoing area of a target just visible at 50 km. is of the order of 0.5 m^2. The effective radar cross-section, σ , for the strongest echoes (those visible at 50 km. or more) is therefore of the order of 0.5 m^2.

The character of the echoes on the PPI and height-range display tubes - e.g. similarity to aircraft echoes - suggests that the echoes at 10 mi. range certainly, and probably less, are received from a volume smaller than that comprised by the beam widths and half-pulse length of the equipments used i.e. at 10 mi. a volume approximately 400 x 400 x 300 m^3 (the beam widths being taken as $1\frac{1}{2}^o$ in both the vertical and horizontal planes, since the echo is equally defined on the PPI and height-range equipments, and the pulse duration is 2 microsec.). In equation I, therefore, we shall certainly over-estimate A by putting A = 400 x 400 m^2 and may still be over-estimating if we take A = 10^4 m^2. If we put $\delta R = \lambda/4 = 2.5$ cm, $\sigma = 0.5$ m^2, A = 10^4 m^2, we have by substitution in I,

$$\frac{d(n-1)}{dR} = \pm 2.51.10^{-4}\ m^{-1}. \qquad \text{II}$$

Now $$(n-1).10^6 = \frac{79}{T}(p - e/7 + 4800e/T)$$

where T is the absolute temperature, p the atmospheric pressure (mb.) and e the vapour pressure (mb.). Differentiating with respect to R and putting reasonable values for T, p and e of T = 273°A., p = 900 mb., e = 5mb. for a normal echo height of the observations reported in this paper, we have:

$$10^6\frac{d(n-1)}{dR} = .29\frac{dp}{dR} + 5.05\frac{de}{dR} - 1.14\frac{dT}{dR}$$

From II $10^6\frac{d(n-1)}{dR} = \pm 2.51.10^2 m^{-1}$ over a distance of 2.5 cm. Over such a distance we can assume $\frac{dp}{dR} = 0$ and so we have $5.05\frac{de}{dR} - 1.14\frac{dT}{dR} = \pm 2.51.10^2$ III

/Changes

Changes in vapour pressure and temperature occurring in 2.5 cm. which satisfy III are shown in Table II.

TABLE II

Changes in vapour pressure (δe) and temperature (δT) which must occur in 2.5 cm. to satisfy equation III

δe (mb.)	± 3.0	± 2.5	± 2.0	± 1.5	± 1.0	± 0.5	∓ 0.5
δT (°C.)	± 7.8	± 5.6	± 3.4	± 1.2	∓ 1.1	∓ 3.3	∓ 5.5 ∓ 7.7

The changes shown in Table II are large but may not be impossibly so. Records of ultra-rapid thermometers do show large fluctuations but accurate measurements to so fine a scale have not yet been made. The principal difficulty in explaining the echoes by such changes in temperature and vapour pressure is rather in the large area over which the changes must persist, and a decrease in the area would lead to a requirement of even greater changes in vapour pressure and/or temperature. Thus if the area over which the variation in refractive index took place was a square of side 50m. the values of δe , δT in Table II would need to be increased fourfold. While such values may still be just feasible it is clear that if a single inhomogeneity accounts for a single echo at a range of 50 km. the area perpendicular to the radar beam must be of the order of 10^3 to 10^4 m^2. If the echo received is the resultant of a number of discontinuities over smaller areas it is difficult to see why the radar echo as seen on the display tube is not then continuous instead of in the form of isolated spots, although, as photograph (iv) shows, continuous echo may sometimes develop after isolated spots have been seen.

It is worthy of note that the echoes usually occur at about the same height and that this height is often about the height of an inversion or isothermal layer. The echoes received cannot be due to scattering from a uniform horizontal layer since the echoes would not then be isolated in character, but this correlation of echo height with inversion height suggests that the echoes may be due to disturbances in the horizontal layer. Many inversions in the atmosphere are very sharply defined with warm dry air overlying colder moist air; e.g. at 1500 GMT at Larkhill on 10th March, 1952 - one of the days on which these echoes were observed - an inversion of temperature of 2°F. took place in 300 ft. (from 3350 - 3650 ft.) as measured by the radiosonde, while within 50 mb. the dew point had fallen from 34°F. to 11°F. - a fall in vapour pressure of about 4 mb. It is not difficult to imagine that, since the radiosonde balloon was rising at 1000 ft/min., the magnitude of the inversion of temperature may well have been more than 2°F. over a distance much less than 300 ft. and that the change in vapour pressure of 4mb. occurred equally quickly. What the changes were on this occasion over a vertical distance of only 2.5cm. is, of course, pure speculation.

Alternatively the fact that the echoes tend to lie in a horizontal layer near the height of an inversion may possibly be explained by regarding the echoes as being received from "bubbles" of warm dry air rising through a cold relatively moist environment (or warm moist air through a cold relatively dry environment). The inversion height would then set a limit to the vertical movement and therefore be the maximum height from which echoes would be received. This explanation seems unrealistic because (i) echo numbers increased and remained high long after convection must have ceased, (in fact increasing stability favoured echo appearance) (ii) two separate layers of echo (photograph (iii)) could not be explained, (iii) the "bubbles" could only move with the wind speed. The fact that the echoes moved faster than the wind speed remains a difficult feature to explain on any theory.

References.

(i) Kerr: "Propagation of short radio waves", Vol.13 of Radiation Lab. Series. Chapter 7 by H. Goldstein. p. 593.

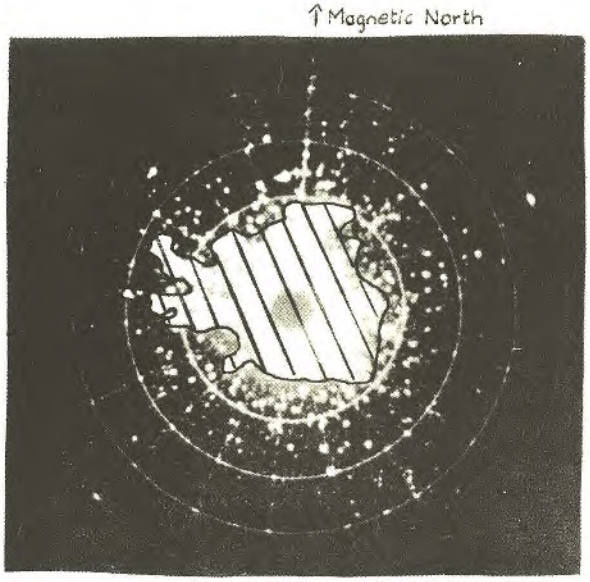
TABLE I

Unusual Radar Echoes observed at East Hill

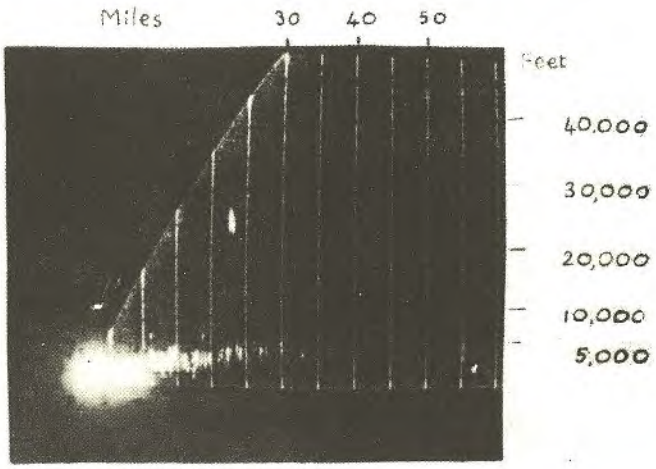
e	Time (GMT)	Height (feet)	Direction (°T) and speed (kt.) of movement of echoes	Probable upper wind	Height of inversion or isothermal layer				Remarks
					Larkhill		Hemsby		
					Time (GMT)	Height (feet)	Time (GMT)	Height (feet)	
/51	1700 -1800	0 to 5,000	-	345°T 25kt. at 5,000ft.	1500 2100	7100 - 8300 0 - 700 700 - 1000 6800 - 8000	1500 2100	0 - 600 6200 - 6600	Clear skies, many pin-point echoes.
52	1730 -1800	3,000 to 5,000	010°T 40kt. approx.	350°T 40kt. at 5,000ft.	1500 2100	0 - 800 4280 - 4720 0 - 800	1500 2100	6000 - 6400 0 - 300	Clear skies.
2	1800 -1900	3,000 to 4,000	345 - 350°T possibly 25 - 30 kt.	310°T 27kt. at 4,000ft.	1500	None	1500	None	Clear skies. Few echoes.
52	1540 -1845	4,000 to 5,000	260 - 290°T probably 40 - 45 kt.	310°T 20kt. at 5,000ft.	1500	5240 - 6200 6200 - 8760	1500	3630 - 5210	Variable cloud, mainly large amounts of Sc.
52	1000 -1100 1655 -1727	500 to 2,000 3,000	250 - 290°T about 60 kt. 290°T 45 kt.	290°T 20kt. at 2,000ft. 290°T 20kt. at 3,000ft.	1500	3480 - 5450	1500	2630 - 3530 5600 - 6350 8040 - 8430	Few echoes. One echo followed for 32 min. Mainly cloudy, 7/8-8/8 Sc.
52	1720 -1840	3,000 to 5,500	Variable about 65 kt.	285°T or variable 10-15 kt. at 3 - 5,000ft.	1500	3280 - 4110	1500	2700 - 3370 9350 - 9600	Several echoes. Cloudy.
2	0950 -1200 1730 -1740 2030 -2220	2,000 to 3,000 2,000 to 5,000 2,500 to 9,500	270 - 290°T 50 - 55 kt. 260 - 270°T 55 - 60 kt. 255 - 285°T 40 - 50 kt.	280°T 25kt. at 2,000ft. 260°T 25kt. to 6,000ft. 270°T 25kt. to 8,000ft.	1500	6160 - 7050	1500	None	Immediately in rear of frontal echo. Broken cloud, many echoes. Large clearances in cloud. Very extensive echoes in layers

507(a)/PN/7/52/40

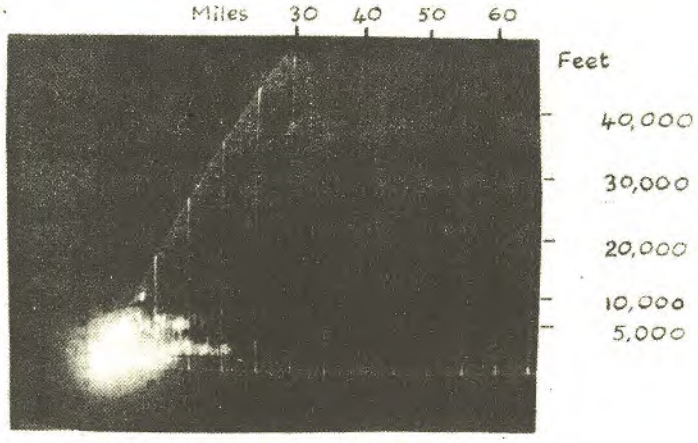
te	Time (GMT)	Height (feet)	Direction and speed of movement of echoes	Probable upper wind	Height of inversion or isothermal layer Larkhill Time (GMT)	Larkhill Height (feet)	Hemsby Time (GMT)	Hemsby Height (feet)	Remarks
52	1000 -1200	0 to 5,000	250 - 260°T 50 - 60 kt. 280°T 35kt.	230°T 20 - 25kt.	0300	9710 -10,700	0300	0 - 960 960 - 2080 6000 - 6950	Followed weather echoes moving east and gradually died out from the west.
					1500	3710 - 4630	1500	9220 - 9850	
/52	1000 -1230	2,000 to 4,000	300 - 310°T 40 - 45 kt.	310°T 18 - 24kt.	0300	2340 - 3250	0300	0 - 610 610 - 1180 3520 - 4360	Numerous echoes. Weak ridge of high pressure. Variable cloud.
					1500	3350 - 3650	1500	4510 - 5000 8880 - 9260	
/52	1100 -1400	2,000 to 5,000	290 - 300°T 50 - 60 kt.	290-300°T 23 - 28 kt.	0300	1700 - 3120	0900	1580 - 3000 3000 - 3250	Very many echoes. Few at 1100 but developed rapidly in next 30 min. Weak cold front with clearance of cloud moved SE as echoes developed.
	1730 -1740	0 to 3,000	285 - 290°T 50 - 55 kt.	310°T 20 - 30 kt.	1500	9750 -10750	1500	7210 - 8050	
/52	1030 -1200	4,000 to 5,000	270 - 285°T 36 - 45 kt.	305 - 310°T 13 - 17 kt.	0300	6750 - 7760 8630 - 9370	0300 0900	6420 - 7490 5520 - 6310 6310 - 6730	Pin-point echoes. Mainly cloudy, weak ridge ahead of warm front.
	1730 -1800	2,000	235 - 260°T 45 - 63 kt. (one from 295°T 45 kt.)	About 240°T 20 kt.	1500	2890 - 3500 3500 - 4810 6900 - 7860	1500 2100	4950 - 5550 8900 - 9460 0 - 1420 1760 - 2610 3790 - 4100 4710 - 6100 7610 - 8070	Pin-point echoes ahead of warm front weather echoes.
/52	1030 -1130	3,000 to 5,000	270 - 280°T 85 - 90 kt.	280°T 45 kt.	0300	3340 - 4630	0300 0900	2990 - 4180 5350 - 6000	Few pin-point echoes ahead of cold front moving SE.



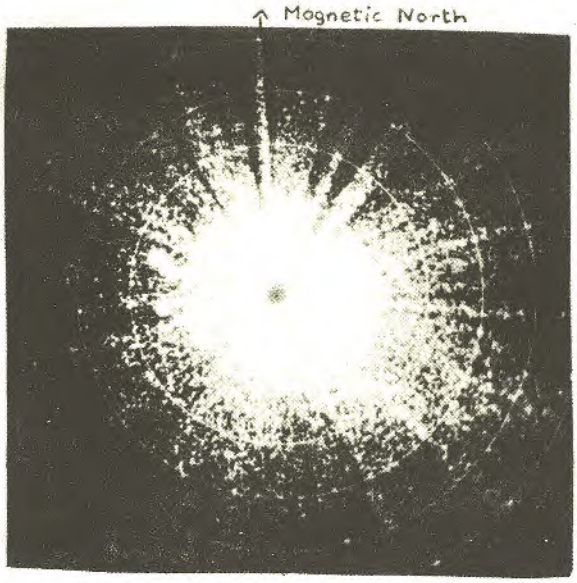
Photograph (i) — P.P.I.
12 54 G.M.T. 20th MARCH 1952
First visible range marker at 10 miles. Shaded area — permanent echoes.



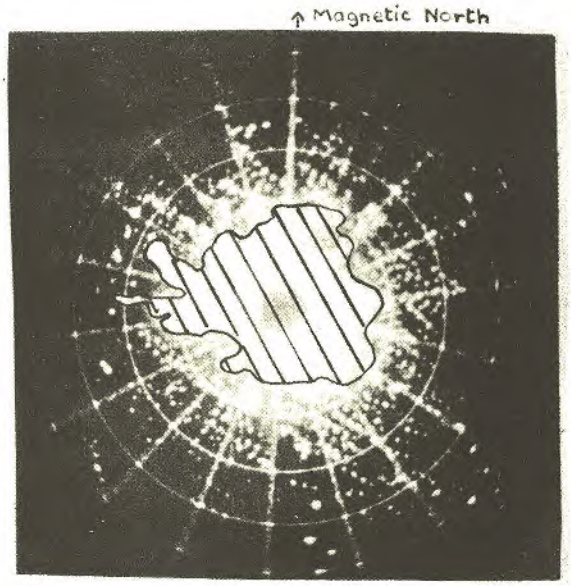
Photograph (ii) — H.R.T.
11 38 G.M.T. 20th MARCH 1952
Bearing 021° Mag.



Photograph (iii) — H.R.T.
21 50 G.M.T. 5th MARCH 1952
Bearing 035° Mag.



Photograph (iv) — P.P.I.
2152 G.M.T. 5th MARCH 1952
Farthest range marker — 30 miles



Photograph (v) — P.P.I.
Time exposure — 4 revolutions of aerial
12 58.35 13 02.49 G.M.T. 20th MARCH 1952

UNUSUAL RADAR ECHOES OBSERVED AT EAST HILL

Note added 30/4/56 to M.R.P. 741

A possible explanation of the fact that these echoes moved faster than the wind speed at their height lies in a reflection mechanism. If the individual echo is received from an object on the ground by reflection from an atmospheric inhomogeneity at height h and range r then on the height range radar display the echo will appear to be at range 2r and height 2h. If the reflecting surface is moving at speed v then the echo will appear to move at speed 2v. The reflecting surface cannot be an extensive layer since reflection at such a layer would not result in a discrete "pin-point" echo but would give a continuous area of echo. It will be seen from Table I that many echoes did move at approximately twice the speed of the wind but the height of the reflecting element must frequently have been much lower than the inversion or isothermal layer indicated. The double layer illustrated in photograph (iii) could then be explained by a "double hop" mechanism with two reflections at atmospheric inhomogeneities since the inhomogeneities on this occasion would appear to have been occurring in great numbers over a wide area. It may be that on some occasions echoes were received both by direct back-scattering and by the reflection process.

The difficulty in this explanation envisaging reflection lies in the very low value of reflection coefficient on present theory since in radar two (or for "double hop", four) reflections at the inhomogeneity are involved as well as the attenuation of the signal by range and the losses on scattering at the ground.